To appear in ApJ

Limits on the event rates of fast radio transients from the V-FASTR experiment

Randall B. Wayth and Steven J. Tingay

International Centre for Radio Astronomy Research, Curtin University. GPO Box U1987, Perth WA, 6845. Australia

randall.wayth@icrar.org

Adam T. Deller

ASTRON, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands

Walter F. Brisken

NRAO, PO Box O, Socorro, NM 87801, USA

David R. Thompson, Kiri L. Wagstaff and Walid A. Majid

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

ABSTRACT

We present the first results from the V-FASTR experiment, a commensal search for fast transient radio bursts using the Very Long Baseline Array (VLBA). V-FASTR is unique in that the widely spaced VLBA antennas provide a discriminant against non-astronomical signals and a mechanism for the localization and identification of events that is not possible with single dish or short baseline interferometer searches for fast transients. Thus far V-FASTR has accumulated over 1700 hours of observation time with the VLBA, between 90 cm and 3 mm wavelength (327 MHz - 86 GHz), providing the first limits on fast transient event rates at high radio frequencies (>1.4 GHz). V-FASTR has blindly detected individual pulses of six known pulsars but has not detected any single-pulse events that would indicate high redshift impulsive bursts of radio emission. At 1.4 GHz, V-FASTR puts limits on fast transient event rates comparable with the PALFA survey at the Arecibo telescope, but generally at lower sensitivities, and comparable to the "fly's eye" survey at the Allen Telescope Array, but with less sky coverage. We also illustrate the likely performance of the Phase 1 SKA dish array for an incoherent fast transient search fashioned on V-FASTR.

Subject headings: methods: observational — pulsars: general — radio continuum: general

1. Introduction

High time resolution probes of the Universe at radio wavelengths, which were historically generally focused on the study of pulsars, are increasingly being employed in the search for short duration (< 1 s) single pulses of radio emission ("fast transients") from explosive events in the nearby or distant Universe. A series of recent intriguing observations of apparently highly dispersed fast transients (Lorimer et al. 2007; Keane et al. 2011; Bannister 2012) suggest an astronomical origin for these events, but the use of single dish radio telescopes precludes the precise localization of these events on the sky and the pursuit of the underlying physical mechanisms driving them. Meanwhile, events having superficially similar characteristics analysed by Burke-Spolaor et al. (2011), suggest a non-astronomical origin. Again, the limitations of single dish radio telescopes make these events difficult to interpret. Explosive events of this type at extragalactic distances would indicate extreme physical conditions (Macquart et al. (2010) and Siemion et al. (2012), and references therein provide excellent summaries of known and possible exotic source populations) and the dispersed impulsive radio emission would allow the direct measurement of the column of ionized material between the event and Earth when a host galaxy of the source can be unambiguously identified, including contributions from the intergalactic medium and the interstellar media in our Galaxy and the host galaxy. Hence, observations of fast radio transients could provide one of the few possible probes of the ionised intergalactic medium, which is believed to comprise more than half the baryons in the local universe (Nicastro et al. 2008).

As a method of unambiguously detecting fast transients and locating them on the sky, Wayth et al. (2011) and Thompson et al. (2011) recognise the power of interferometric arrays of widely spaced radio telescopes, which are robust to local radio frequency interference posing as astronomical radio emission and provide a simple means of localizing and identifying events of an astronomical origin. Wayth et al. (2011) and Thompson et al. (2011) describe an experiment for the detection and localization of short timescale, dispersed sources of radio emission, V-FASTR, using the Very Long Baseline Array (VLBA). The utility of interferometric telescopes for the detection and localisation of this class of event has prompted the development of new methods of detecting fast transients using interferometers (Siemion et al. 2012; Bannister & Cornwell 2011; Law & Bower 2012). Interferometer-based experiments are planned or underway at LOFAR (Stappers et al. 2011), the GMRT (Bhat 2011), ASKAP (Macquart et al. 2010), the MWA (Lonsdale et al. 2009) and the ATA (Siemion et al. 2012;

Law et al. 2011). Experiments such as V-FASTR are important to help establish the rate of dispersed pulses as a pointer to the design of experiments with the next generation of radio telescopes with wide fields of view, along with theoretical analyses (Macquart 2011), eventually leading to experiments using the SKA.

In this Letter, we present the results of the first nine months of V-FASTR data collection from commensal analysis of regular VLBA observations.

2. Observations

The V-FASTR experiment and initial trial observational results have previously been described by Wayth et al. (2011) and Thompson et al. (2011); the reader is referred to these papers for a detailed description of the V-FASTR system running commensally at the VLBA. V-FASTR has been undertaken under VLBA proposals BT100, BT111, BT118 (P.I. Tingay) and BM348 (P.I. Majid).

VLBA data are correlated at the Array Operations Center in Socorro, NM. During correlation, spectrometer data are generated with time resolution between 1 ms and 2 ms. In the detection stage of the system the dedispersed time series is time averaged over two, four and eight time steps to provide maximum sensitivity to pulses with intrinsic width between approximately 1 ms and 10 ms. Based on previous evidence from Lorimer et al. (2007) and Keane et al. (2011), 10 ms was deemed a sufficient upper value for the averaging time, especially at frequencies above 1.4 GHz where the effects of scattering broadening decrease dramatically. Trial dispersion measures between 0 and 5000 cm^{-3} pc are used. The VLBA's total observing bandwidth can optionally be split into several non-contiguous sub-bands, so the spacing between trial dispersion measures (DMs) is tailored to each observation's maximum and minimum frequency and integration time.

About half of all VLBA observations employ standard continuum observing modes. There are several other VLBA observing modes that the V-FASTR pipeline can process with full effectiveness, as briefly described below, making up the vast majority of the remaining half of the observing time. One class of observation can make use of two receivers simultaneously. Specifically, the 2.4 GHz and 8.4 GHz receivers are used as a pair in geodetic observations; the V-FASTR pipeline does not discriminate based on the dual-band configuration and will completely search DM-space just as for any other observation, treating the split band as a single band. Second, pulsar experiments often employ a "gate" to disable accumulation of cross correlations during the off-phases of the pulsar. In the DiFX correlator (Deller et al. 2007, 2011), the auto correlations are not affected by the gate and thus from the perspective of V-FASTR, the data look the same as continuum data. Finally, some observations target spectral lines, some of which are strong enough to affect the observed band-pass. By design the V-FASTR system automatically subtracts stable spectral features before dedispersion is performed, so the presence of spectral lines does not affect performance.

3. System performance

Some pulsars trigger the detector and serve as good tests of the system. V-FASTR blindly detected pulsars J0157+6212, J0332+5434, J0826+2637, J1136+1551, J1607-0032 and J1935+1616 during normal operations at the correct DMs. It is worth noting that pulsars J0157+6212 and J0826+2637 have a mean peak flux density of 140 mJy and 500 mJy respectively (Lorimer et al. 1995; Manchester et al. 2005), which is below our detection threshold. In these cases, a small number of individual pulses substantially exceeded the average flux density and were caught by the system. Either intrinsic pulse to pulse variation or strong diffractive interstellar scintillation could be responsible for this effect.

We have used detections of real astrophysical transients (pulsars) to tune our thresholds for the triggering and coherent follow-up of candidate events. To date, V-FASTR has amassed thousands of detections of individual pulses with detection signal-to-noise ratio (SNR) of 5 or greater. Using captured baseband data, we can reliably obtain antenna delay solutions using the AIPS task FRING for events with a detection SNR as low as 8. Using these delay solutions, we can recover the position of the transient source at the level of several arcseconds without external calibration data (Wayth et al. 2011). Delay solutions can sometimes be obtained from lower detection SNR events, but success is not guaranteed. Based on this experience, we set the SNR threshold to follow up events to be 7σ. At the 7σ level, we typically receive of order 1-10 candidate events per day, and so this threshold is also logistically feasible for candidate inspection and classification, as described fully in Wayth et al. (2011) and Thompson et al. (2011), and briefly below.

Interference at one or more stations can be a significant practical bottleneck to survey sensitivity. V-FASTR uses adaptive noise reduction to accommodate its diverse system configurations and observing frequencies. A multi-station detection strategy (Thompson et al. 2011) distinguishes local interference from true astronomical events using geographically distributed VLBA stations; it models separate stations as independent measurements of a common signal, with an independent interference process at each station producing sporadic additive noise events. A robust statistical estimator excises one or more stations' extreme values at each new time step; such strategies have been shown to improve the effective sensitivity for a fixed budget of false triggers.

Noise conditions determine the optimal number of stations to excise. Satellites or other local radio frequency interference (RFI) can coincidentally appear at more than one station simultaneously, and under these conditions optimal sensitivity requires removal of multiple streams per timestep. However, the intrinsic sensitivity is reduced as more extreme values are removed, so determining the appropriate excision level for each new observation is tantamount to a one-parameter optimization. We set this value on-line during the detection process by periodically injecting synthetic pulses into the datastream just before the incoherent de-dispersion step. These pulses are injected at known intervals and dispersion measures with SNRs ranging from 5 to 9. A self tuning system tests excision levels between 0 and 4 stations, using the value which results in the best retrieval rate for injected pulses before the first false candidate trigger. We re-estimate the optimal excision level every 10000 timesteps during the scan to handle time-varying noise.

Following the automated steps described above, the 1-10 resultant candidate events each day are manually inspected to determine the likelihood of an astronomical origin. If deemed astronomically plausible, the data can then be reprocessed incoherently or coherent and imaged as described above as final confirmation.

4. Results and discussion

Other than the detections of known pulsars, V-FASTR has not detected any single radio pulses to date. Table 1 summarizes the number of hours of data processed by the V-FASTR system, grouped by VLBA receiver band (restricted to VLBA observations with 64 MHz bandwidth), along with various system parameters and order-of-magnitude upper limits on the event rate of fast transients assuming sources are isotropically distributed and a simple top-hat primary beam model for the VLBA antennas.

Following the treatment of fast transient event rates and amplitudes for the PALFA survey (Deneva et al. 2009), we calculate similar limits derived from the V-FASTR data, using a realistic primary beam model. Some differences between the PALFA and V-FASTR surveys need to be recognised. For example, PALFA used a seven beam receiver on Arecibo, whereas V-FASTR uses the ten distributed antennas of the VLBA, leading to some modification of how event rate and minimum sensitivity are calculated for V-FASTR compared to PALFA. A significant difference between the calculation of Deneva et al. (2009) and the calculation presented here is that Deneva et al. (2009) ignore the contribution to the event rate provided by the near sidelobes of the Arecibo antenna. For the work presented here, we have included the event rate contribution due to the first and second sidelobes of the VLBA antennas (assuming circularly symmetric sidelobes), with 0dB far sidelobes the sole contributor to the event rate constraint beyond the 3^{rd} null of the VLBA beam. The inclusion of the contributions due to the first and second sidelobes has the effect of significantly improving the event rate constraint at sensitivities two orders of magnitude worse than the boresight sensitivity, by virtue of the large solid angle subtended by those sidelobes.

Figure 1 shows the V-FASTR event rate limits relative to the PALFA limits, based on the data presented in Table 1 for the V-FASTR 20 cm observations. In addition to the information in Table 1, the following characteristics of the VLBA antennas have been used in the limit calculations: fraction of hemisphere covered by far sidelobes = 0.5; antenna efficiency = 0.7.

At event flux densities greater than 600 mJy (10 ms integration), the PALFA and V-FASTR limits on event rate are very similar. It should be noted that the apparent improvement at low sensitivity for V-FASTR is largely a function of including the contributions of the first and second sidelobes, which are not included in the PALFA limits. Beyond this difference there is a marginal improvement for V-FASTR over PALFA, at low sensitivity, due to the smaller VLBA antennas relative to Arecibo. The limits provided by the far sidelobes for PALFA and V-FASTR are coincidentally very similar, because the VLBA consists of ten antennas and because the PALFA constraint assumes the far sidelobes cover the full hemisphere, whereas for V-FASTR we assume a hemispheric coverage of 0.5, chosen because the VLBA antennas are steerable and in most pointing directions the ground will cover a significant fraction of the far sidelobes.

While the PALFA survey is an example of a narrow/deep survey, an example of a wide/shallow survey is the Allen Telescope Array (ATA) "fly's eye" survey (Siemion et al. 2012), which covered 150 deg^2 of sky over a period of 450 hr at a frequency of 1.4 GHz and with a sensitivity of 44 Jy (at the same averaging period of 10 ms). Figure 1 also shows the limits arising from the ATA experiment, which do reach the order of event rate implied by Lorimer et al. (2007) and Keane et al. (2011), but do not report the detection of any similar events above their sensitivity threshold.

We follow Figure 11 of Siemion et al. (2012) and indicate a number of fiducial points on Figure 1, including the rates infered from the suggested extragalatic events reported by Lorimer et al. (2007) and Keane et al. (2011), as well as the same event rates (per Gpc^{-3}) for Gamma-Ray Bursts and core collapse supernovae as cited by Siemion et al. (2012).

While our limits at 1.4 GHz have not yet reached the fiducial points shown in Figure 1, V-FASTR observations are accumulated in commensal fashion and the limits will change in two ways. First, because of the pending high bandwidth upgrade to the VLBA, the limit curve will move to higher sensitivities (move down in Figure 1), by approximately a factor of three. Second, as more time is spent on sky (currently at a rate of 100 - 200 hr/month at 1.4 GHz), the limit curve will move to exclude less frequent events (to the left in Figure 1). From Figure 1, it can be seen that with the sensitivity upgrade and a factor of $\sim$10 increase in observing time, V-FASTR will be reaching an interesting region of parameter space in terms of the events reported by Lorimer et al. (2007) and Keane et al. (2011) at 1.4 GHz.

However, Figure 1 only reflects the aggregate V-FASTR dataset at 1.4 GHz, representing 31% of the total V-FASTR dataset. One significant strength of the V-FASTR experiment is that the VLBA operates at frequencies above 1.4 GHz and we can thus derive the first limits on fast transient event rates at frequencies higher than $\sim$1.4 GHz. Figure 2 shows limits derived in the same manner as above for V-FASTR data at 4 cm, 2 cm, 1 cm and 7 mm, representing 13%, 13%, 22% and 10% of the total V-FASTR dataset, respectively. The remaining percetage of time is dominated by the first observations made using the new VLBA wideband system, which will be reported separately in a future publication.

The characteristics of RFI at the VLBA vary across the spectrum and is somewhat different in nature at the different VLBA sites[1]. Most continuum observations make use of standard frequency setups that avoid the worst. Generally speaking, RFI is worse at lower frequencies where antenna directivity is lower, stray signal scattering is more effective, and transmitters tend to be stronger and more numerous. Fortunately, most intermittent RFI can be distinguished from signals of interest at low RFI by the lack of dispersion sweep. Above 20 GHz RFI is virtually unknown and would be dominated by continuous tones entering the VLBA signal chain post down-conversion. Between 4 and 20 GHz intermittent narrow-band RFI is occasionally seen. RFI at these frequencies tends to be local to individual sites. Most RFI encountered at the VLBA is seen in the 20 cm and 13 cm bands (between 1 and 3 GHz) where constellations of satellites (e.g., GPS, Glonass, Iridium, and satellite radio) tend to transmit. It is in these bands that the signal classification methods employed in this work are both most effective and most necessary.

Event rate limits derived in Table 1 assume an isotropically distributed source population, in which case any telescope pointing direction is as likely to see an event as any other. In practise, where the VLBA is pointed depends strongly on the observing frequency. 20 cm observations often point at pulsars so are biased towards the Galactic plane, whereas 4 cm observations mostly observe quasars away from the plane. Figure 3 shows the sky coverage of the V-FASTR observations listed in Table 1 combined over all receivers. There

[1]http://www.vlba.nrao.edu/astro/rfi/

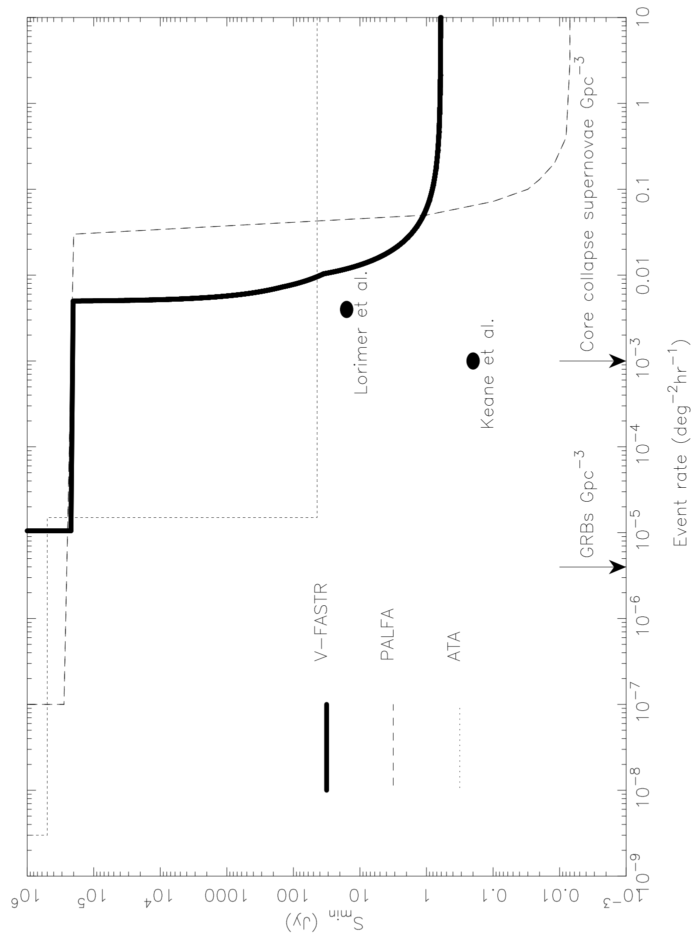

Fig. 1.— V-FASTR event rate limits (solid line) at 1.4 GHz compared to limits also at 1.4 GHz from Deneva et al. (2009) (dashed line) and Siemion et al. (2012) (dotted line). The event rates inferred from the Lorimer and Keane bursts are shown, as are the event rates for GRBs and core collapse supernovae used by Siemion et al. (2012).

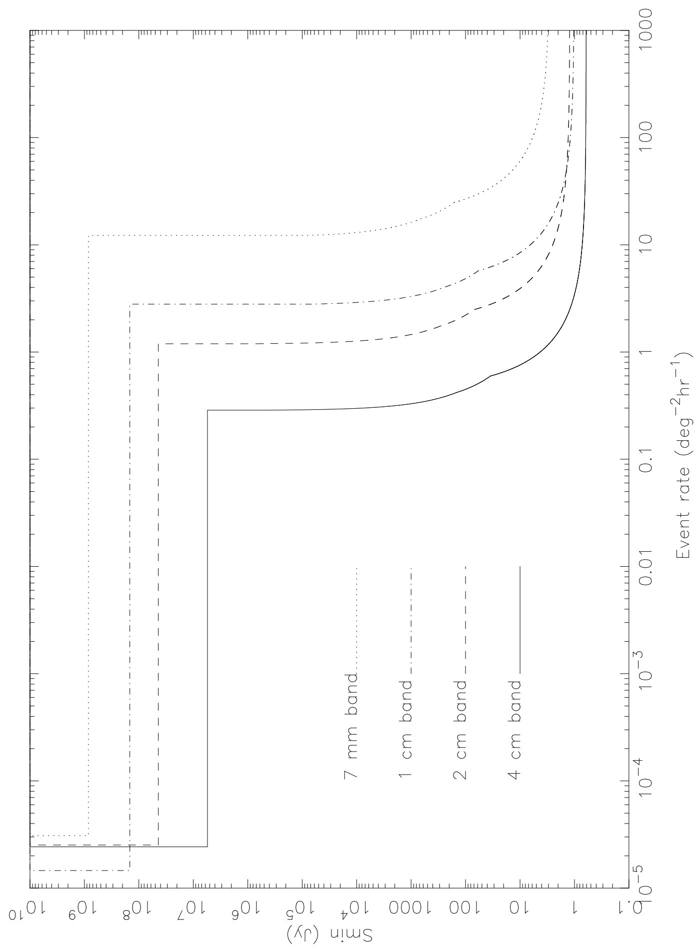

Fig. 2.— V-FASTR event rate limits for the 4 cm, 2 cm, 7 mm, and 3 mm bands

are observations roughly equally distributed over the entire sky visible to the VLBA, plus an over-density of observations along the Galactic plane. Pulse broadening due to ionised material in the Galactic plane could potentially bias our results. To check the magnitude of this effect, we used the NE2001 Galactic free electron density model (Cordes & Lazio 2002) to calculate the expected pulse broadening of each observation assuming the source is at a distance of 1 Mpc. In only 2% of our observations would an extragalactic pulse have been scatter-broadened more than 1 ms, so we conclude that this is not a significant source of error, given that we are sensitive to pulses up to 10 ms duration.

Given the paucity of information for the fast transient events thus far detected with single dish experiments (Lorimer et al. 2007; Burke-Spolaor et al. 2011; Keane et al. 2011) due to very limited angular resolution, the fact that they have all been detected with a single instrument (Parkes radio telescope), and all in a single observing band (20 cm), obtaining a diversity of search parameters is very important for future investigations of fast transients. In particular, without knowledge of the spectral index distribution of fast transients, searches across a wide range in frequency, such as provided by V-FASTR for the first time, are required.

While the existence of fast radio transients as a signature of high energy explosive events at cosmological distances is uncertain, the science return from detecting and localizing even a small number of such astronomical events is extremely high. As a unique and direct probe of the intergalactic medium, we could learn much about the reservoir of baryons believed to reside between the galaxies. V-FASTR, as an activity that proceeds commensally with the regular observations of an interferometric array, is a low cost and highly efficient method of probing the poorly explored parameter space of fast transient searches, with the ability to both detect and, crucially, localize on the sky any events of an astronomical origin. V-FASTR is thus a trailblazer for what is possible in the future for new interferometric instruments under development, in particular the SKA and its Precursors and Pathfinders. These large and sensitive interferometers, if designed such that high time and frequency resolution autocorrelation data can be accessed in parallel to the regular processing signal path in real time, will be able to support V-FASTR style experiments.

With the high sensitivities and very wide fields of view planned for the next-generation instruments, V-FASTR style experiments will make rapid in-roads into the parameter space shown in Figures 1 and 2. To illustrate this point, Figure 4 shows a comparison between the results of the PALFA survey and the expected results of a commensal fast transient survey between 1 and 2 GHz with the Phase 1 SKA (SKA_1) dish component, using the SKA_1 specifications listed in Dewdney (2010) and the same survey duration as PALFA, 461 hr. SKA_1 will consist of 250×15 m dish antennas distributed over $\sim$100 km with single pixel

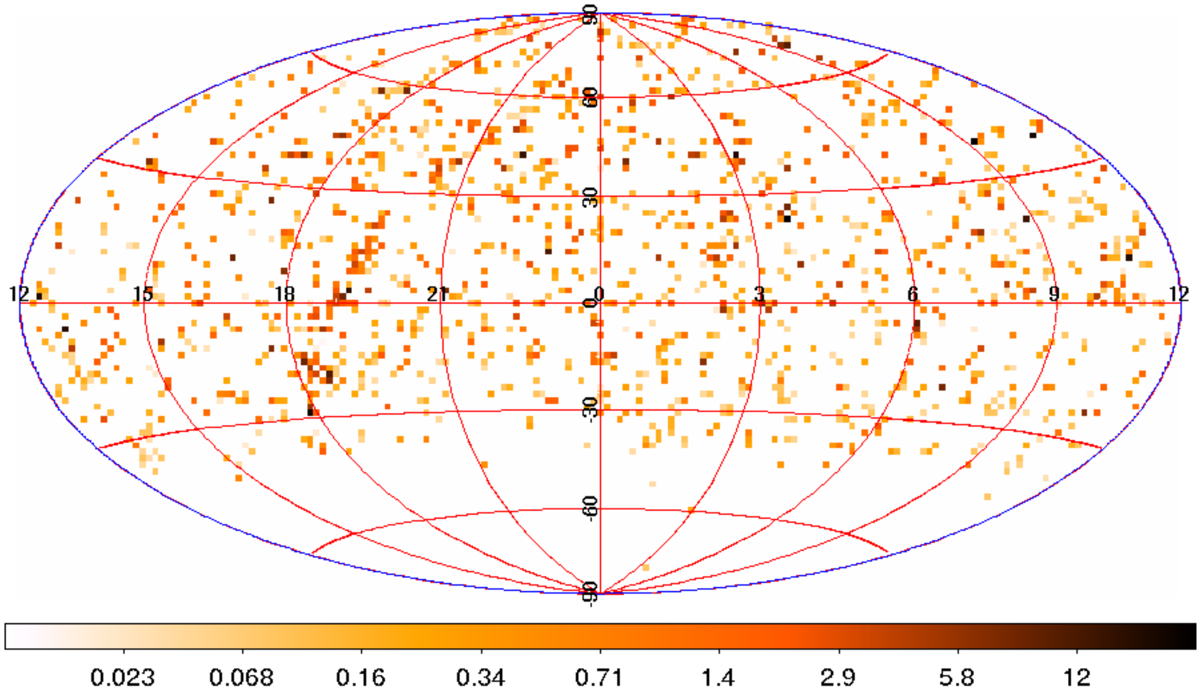

Fig. 3.— Combined time observed per square degree of sky over all VLBA receivers (colorbar indicates observation time in hours). The sky is shown in equatorial coordinates.

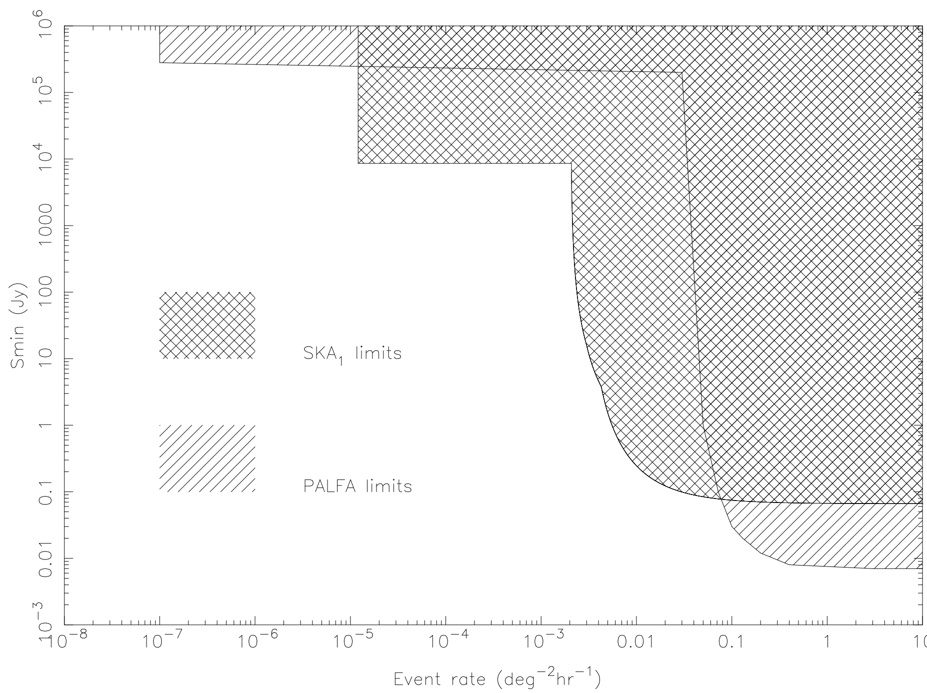

Fig. 4.— Event rate limits for the Phase 1 SKA dish array after 461 hours between 1 and 2 GHz using a V-FASTR style system (cross-hatched), compared to the event rate for PALFA from Deneva et al. (2009) (hatched).

feeds, with collecting area equivalent to a ∼110 m single dish. An incoherent V-FASTR style fast transient survey with SKA_1 will thus not reach the maximum sensitivity of PALFA, even with the larger bandwidth of SKA_1. However, the larger field of view of SKA_1, due to the small dish diameter, allows more than an order of magnitude improvement in event rate limits. After ∼4000 hours, the event rate limit provided by SKA_1 would almost cover the combined rate and luminosity implied by Lorimer et al. (2007) and Keane et al. (2011) and will retain the crucial localisation characteristic of the V-FASTR experiment, as a highly distributed array, although not with VLBA-scale antenna spacings. Furthermore, the novel signal detection algorithms deployed for V-FASTR (Thompson et al. 2011) are likely to be useful to large-scale future instruments, including the SKA.

The International Centre for Radio Astronomy Research is a Joint Venture between Curtin University and The University of Western Australia, funded by the State Government of Western Australia and the Joint Venture partners. S.J.T is a Western Australian Premiers Research Fellow. R.B.W is supported via the Western Australian Centre of Excellence in Radio Astronomy Science and Engineering. A.T.D was supported by an NRAO Jansky Fellowship and an NWO Veni Fellowship. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the US National Aeronautics and Space Administration. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. AIPS is produced and maintained by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of NASA's Astrophysics Data System.

Facility: VLBA.

REFERENCES

Bannister, K. 2012, ApJ, submitted

Bannister, K. W., & Cornwell, T. J. 2011, ApJS, 196, 16

Bhat, N. D. R. 2011, Bulletin of the Astronomical Society of India, 39, 353

Burke-Spolaor, S., Bailes, M., Ekers, R., Macquart, J.-P., & Crawford, III, F. 2011, ApJ, 727, 18

Cordes, J. M., & Lazio, T. J. W. 2002, ArXiv Astrophysics e-prints

Deller, A. T., Tingay, S. J., Bailes, M., & West, C. 2007, PASP, 119, 318

Deller, A. T., Brisken, W. F., Phillips, C. J., et al. 2011, PASP, 123, 275

Deneva, J. S., Cordes, J. M., McLaughlin, M. A., et al. 2009, ApJ, 703, 2259

Dewdney, P. 2010, http://www.skatelescope.org, SKA Memo #130

Keane, E. F., Kramer, M., Lyne, A. G., Stappers, B. W., & McLaughlin, M. A. 2011, MNRAS, 415, 3065

Law, C. J., & Bower, G. C. 2012, ApJ, in press

Law, C. J., Jones, G., Backer, D. C., et al. 2011, ApJ, 742, 12

Lonsdale, C. J., Cappallo, R. J., Morales, M. F., et al. 2009, IEEE Proceedings, 97, 1497

Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Science, 318, 777

Lorimer, D. R., Yates, J. A., Lyne, A. G., & Gould, D. M. 1995, MNRAS, 273, 411

Macquart, J., Bailes, M., Bhat, N. D. R., et al. 2010, PASA, 27, 272

Macquart, J.-P. 2011, ApJ, 734, 20

Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993

Nicastro, F., Mathur, S., & Elvis, M. 2008, Science, 319, 55

Siemion, A. P. V., Bower, G. C., Foster, G., et al. 2012, ApJ, 744, 109

Stappers, B. W., Hessels, J. W. T., Alexov, A., et al. 2011, A&A, 530, A80

Thompson, D. R., Wagstaff, K. L., Brisken, W. F., et al. 2011, ApJ, 735, 98

Wayth, R. B., Brisken, W. F., Deller, A. T., et al. 2011, ApJ, 735, 97

Table 1: V-FASTR sensitivity and event rate limits for VLBA observing bands, as of 2012 March 15.

Receiver	Freq (MHz)	FWHM (arcmin)	SEFD (Jy)	7σ sens (Jy)	Time (hr)	Event rate [a] limit ($\mathrm{deg}^{-2}\mathrm{hr}^{-1}$)
90cm	325	160	$\sim$2200	5	7.6	0.03
50cm	610	83	$\sim$2200	5	0	NA
20cm	1500	34	$\sim$300	0.7	528	0.008
13cm[b]	2200	23	$\sim$300	0.7	169	0.05
6cm	4800	11	$\sim$200	0.5	16	2.7
4cm	8400	6	$\sim$300	0.7	229	0.56
2cm	14000	4	$\sim$600	1	220	1.6
1cm	22000	2	$\sim$500	1	381	2.3
7mm	43000	1	$\sim$1400	3	180	19
3mm[c]	86000	0.6	$\sim$4000	10	19	707

[a] Calculated for the primary beam main lobe only assuming a top-hat response over the FWHM.

[b] This row includes dual 2.4/8.4 GHz geodetic observations

[c] Presently only 8 antennas have a 3mm receiver, which is accounted for in this row.